**Passive and Active Control of Heat Transfer at Interfaces**

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**Co-PIs: Paul Braun, Gang Chen, Chris Dames, Shanhui Fan, Pawel Keblinski, and William King**

**Final Report, September 30, 2013**

Our project encompassed the collaborative work of 7 PIs at 5 leading research universities over the course of 5 years. Our research is reported in 60 refereed journal publications that are listed below. Several more publications have been submitted or are in preparation. Development of human resources includes contributions to the training of 16 graduate students and 10 post-doctoral research associates.

A key transfer of technology to a DoD laboratory was the development of an apparatus for time-domain thermoreflectance (TDTR) measurements of thermal transport properties at AFRL. During the course of the MURI project, TDTR has emerged as the state-of-the-art approach for measurements of the thermal conductivity of thin layers and studies of heat transfer at interfaces. Approximately 20 instruments are in use world-wide that are largely based on the approaches that were refined during the course of the MURI. (We have not been directly involved but understand that an similar instrument is under development at ARL.)

The changes in PI at UC Berkeley require some comment. The original team included Prof. Arun Marjmdar as a co-PI. Arun left Berkeley to become the founding director of ARPA-E shortly after the project started and the leadership of the Berkeley effort was transferred to a research scientist, Dr. Yang Zhao. Dr. Zhao left Berkeley approximately 2 years ago and the PI responsibilities were transferred to a new hire in the Mechanical Engineering Department at UC Berkeley, Prof. Chris Dames.

As the culmination of our collaboration, the 7 original PIs of the MURI joined with 7 of our close colleagues to write an update to the 2003 review "Nanoscale thermal transport." The 2003 review, published in the *Applied Physics Reviews* section of *Journal of Applied Physics* has generated approximately 1000 citations. We have similar high expectations for our new review "Nanoscale thermal transport II: 2003-2013" which will appear in the inaugural issue of *Applied Physics Reviews* as a stand-alone journal in January 2014.

In what follows, we highlight selected examples of our scientific accomplishments. Much of the text is excerpted from our jointly authored review article. The reference numbers refer to the numbered list of MURI publications below.

*I. Thermal conductance of weakly bound interfaces.*

To explicitly study the effect of interfacial bonding character on a heat transfer at an interface, a gold film was transfer-printed to a self-assembled monolayer (SAM) with systematically varied termination chemistries. Using a combination of ultrafast pump-probe techniques (time-domain thermoreflectance and picosecond acoustics) and laser spallation experiments, changes in bonding strength and heat flow at the gold-SAM interface are independently measured and

correlated [38]. It was shown that varying the density of covalent bonds within this single bonding layer modulates both interfacial stiffness and interfacial thermal conductance. Heat transport at Au/SAM/Qz interfaces using SAMs of the same length and different end-groups were studied. The thiol functionality is expected to form a strong covalent-like bond to the gold film while only a weak van der Waals attraction should attach the gold film to the methyl-terminated surface. G = 68 MW $m^{-2}$ $K^{-1}$ for the thiol interface and G = 36 MW $m^{-2}$ $K^{-1}$ for the methyl interface, confirming that interfacial bonding directly impacts thermal conductance. Particularly striking is the similarity between G measured for thiol interfaces and the calculations for a Au/SAM/Si interface with strong bonding at both SAM end-groups [28].

Hsieh continuously varied the strength of interfacial bonding using high hydrostatic pressure in a SiC anvil cell [22]. An Al-graphene-SiC interface was formed on the face of the SiC anvil using transfer printing of a graphene followed by sputter deposition of Al. As the pressure increases from ambient to 10 GPa, the value of G increases by nearly an order of magnitude from G = 30 to G= 200 $m^{-2}$ $K^{-1}$. At high pressures, G for Al-graphene-SiC is the same as G for Al deposited directly on SiC cleaned at high temperatures.

A calculation shows that the interfacial phonon transmission coefficient for a typical phonon representing those carrying the majority of the heat, strongly increases with increasing interfacial stiffness [51]. Furthermore, the transmission coefficient saturates at strong bonding at the value coinciding which by the prediction of the acoustic mismatch model.

### *II. Near-field radiation heat transport*

One of the most significant developments in the past decade for near-field thermal transfer is the developments of techniques that implement fluctuational thermodynamics in a numerically exact fashion in non-planar geometries. The sphere-plate geometry which directly connects to some of the recent experiments, has been solved by Otey and Fan [44]. Direct comparison between numerically exact calculations and the experiment as well as several previously used approximations has been made. The exact calculations correctly reproduced the far-field limit when the sphere-plate separation is significantly larger than the thermal wavelength as well as the results of the dipole approximation when the sphere is small.

The Chen group at MIT developed a sphere-plate experimental configuration to investigate near-field heat transfer [54]. This experimental configuration overcomes the difficulties of maintaining parallelism in the two parallel plates, and unknown tip geometry in the STM experiment. Their experiment took advantage of the proven extreme thermal sensitivity of bi-layer cantilevers used for atomic force microscopes [23,32] which compensates for a smaller area involved in radiative transfer due to the curvature of the sphere compared to the parallel plate configuration. They reported experimental results between a glass sphere and different substrates including glass, silicon, and gold, for sphere and plate separation down to 30 nm. Such experiments were extended to smaller separations and between metallic surfaces [53].

**Publications** (alphabetical order by 1st author). An html database including URL links and abstracts is at http://users.mrl.illinois.edu/cahill/afosr_muri_pubs_table.html


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2. Cahill, D. G.; Braun, P. V.; Chen, G.; Clarke, D. R.; Fan, S.; Goodson, K. E.; Keblinski, P.; King, W. P.; Mahan, G. D.; Majumdar, A.; Maris, H. J.; Phillpot, S. R.; Pop, E. & Shi, L. (2014), 'Nanoscale thermal transport II: 2003–2012', *Appl. Phys. Rev.*, in press.

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**PI Awards and Recognition**

Prof. Paul Braun

1. Named Ivan Racheff Professor of Materials Science and Engineering, 2011.
2. Young Alumnus Award, Department of Materials Science and Engineering at the University of Illinois, 2011.
3. Received Friedrich Wilhelm Bessel Research Award from the Alexander von Humboldt Foundation (Germany), 2011.
4. Recipient of a Xerox Award for Faculty Research, College of Engineering, University of Illinois, 2009.

Prof. David Cahill

1. Fellow, Materials Research Society, 2012.
2. Elected to the cycle of vice-chair, program-chair, chair of the Division of Materials Physics, American Physical Society, 2011-2014.
3. Editorial Board of Applied Physics Letters and Journal of Applied Physics, 2010-2013.

Prof. Gang Chen

1. Fellow, American Physical Society, 2012.
2. Member, National Academy of Engineering, 2010.
3. Fellow, American Association for the Advancement of Science (AAAS), 2009.
4. Carl Richard Soderberg Professor of Power Engineering, 2009.

Prof. Chris Dames

1. NSF CAREER Award, 2011.
2. DARPA Young Faculty Award, 2009.

Prof. Shanhui Fan

1. Fellow, IEEE, 2010.
2. Fellow, SPIE, 2009.
3. Fellow, American Physical Society, 2008.

Prof. Pawel Keblinski

1. School of Engineering Research Excellence Award, Senior Faculty Category, Rensselaer Polytechnic Institute, 2010.

Prof. William King

1. Fellow, American Society of Mechanical Engineers, 2011.
2. Society of Manufacturing Engineers, "Innovations that will Change Manufacturing," 2011.
3. Naval Research Laboratory Edison Award for Innovation, 2010.
4. Best Paper Award, IEEE Sensors Conference, 2010.
5. ASME Bergles-Roshenow Young Investigator Award in Heat Transfer, 2009.
6. R&D 100 Award – “VESTA”- one of the 100 most technologically significant innovations to enter the market, 2008.

**Junior Research Staff working during the last year of the project**

- U. Illinois-Urbana
  - Post-docs: Joe Feser (50%), Jiung Cho; Hanna Cho (50%)
  - Ph.D. candidates: Gyungmin Choi, Greg Hohensee, Beomjin Kwon, Elise Corbin, Matthew Rosenberger
- Berkeley
  - Ph.D. candidates: Kedar Hippalgaonkar, Zhen Chen
- MIT
  - Post-docs: Anastassios Mavrokefalos (50%), Sang Eon Han (50%)
  - Ph.D. candidate: Poetro Sambegoro
- RPI
  - Post-doc: William Evans
  - Ph.D. candidate: Meng Shen
- Stanford
  - Post-doc: Dr. Zongfu Yu (50%)
  - Ph.D. candidate: Clayton Otey

**Placements of MURI-supported students/post-docs**

- Post-docs completed: Karma Sawyer (ARPA-Fellow); Jung-Tsung Shen (Asst. Prof. Wash U.); Mark Losego (NCSU/RTSFI); Zongfu Yu (Asst. Prof. UW-Madison); Joseph Feser (Asst. Prof. U. Deleware); Hanna Cho (Asst. Prof. Texas Tech).
- Ph.D.'s completed: Wah Tung Lau (post-doc, U. Toronto); Sheng Shen (Asst. Prof., CMU); Wen-Pin Hsieh (post-doc, Stanford); Lin Hu (post-doc, CMU); Beomjin Kwon (NIST); Kedar Hippalgaonkar (ASTAR, Singapore).
- M.S. completed, Andrew Hafeli (Nexteer); Ming Zhi Li (Qualcomm).

**Placements of MURI-supported students/post-docs at AFRL**
Jessica Remmert (King's group); Sergei Shenogin (Keblinski's group)

**Placement of student/post-docs from the PI groups at AFRL** (not supported directly by the MURI)
Shawn Putnam (Cahill's group); Abigail Juhl (Braun's group)